DIY Air Cleaners – Tests and observations

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With participation of
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Links to related documents:

- Part 2 of this report
- CADR: Tests, Interpretation and Sizing
- Video on DIY construction and test

1. Background and purpose

- Aerosols are known to be the main transmission route for COVID-19 indoors. Ventilation and air filtration are, therefore, most effective preventive measures. Abundant information available at: twitter.com/jljcolorado
- At least, ACH=5 (air changes per hour) are recommended to duly purify the air in a room (see schools.forhealth.org/ventilation-guide/).
- Apart from commercial air purifiers, there is also another (much) cheaper yet effective solution: the DIY Air Purifier, which can be built by assembling a box fan and a high-efficiency filter (MERV 13=F7 or higher).

  See e.g. www.texairfilters.com/how-a-merv-13-air-filter-and-a-box-fan-can-help-fight-covid-19/, where this image comes from:

- However, although the general idea is clear, there is a lack of detailed data that would be needed for an appropriate selection and use of DIY Air Purifiers.
- For example: flow rate of filtered air obtained with DIY purifier? Size of fan required for a given room? How critical is to seal the filter?...

The objective here is to provide data and info obtained from tests at LIFTEC for some DIY configurations.

Also, if you have any other relevant information, your input would be most welcome.

2. Fans and filters

This is a list of the components that have been used in the tests so far.

- Two box fans:
  - BF1: 40 W, diameter=30 cm (22 €)
  - BF2: 80 W, diameter=50 cm (40 €)
- An open, shroudless fan:
  - OF1: 120 W, diameter=45 cm (30 €)
- Filters:
  - F1": MERV 13 (equiv to F7 / EU7 in Europe), 20"x22"x1" (15 €)
  - Tests with other filter sizes and grades in progress.

BF1

BF2

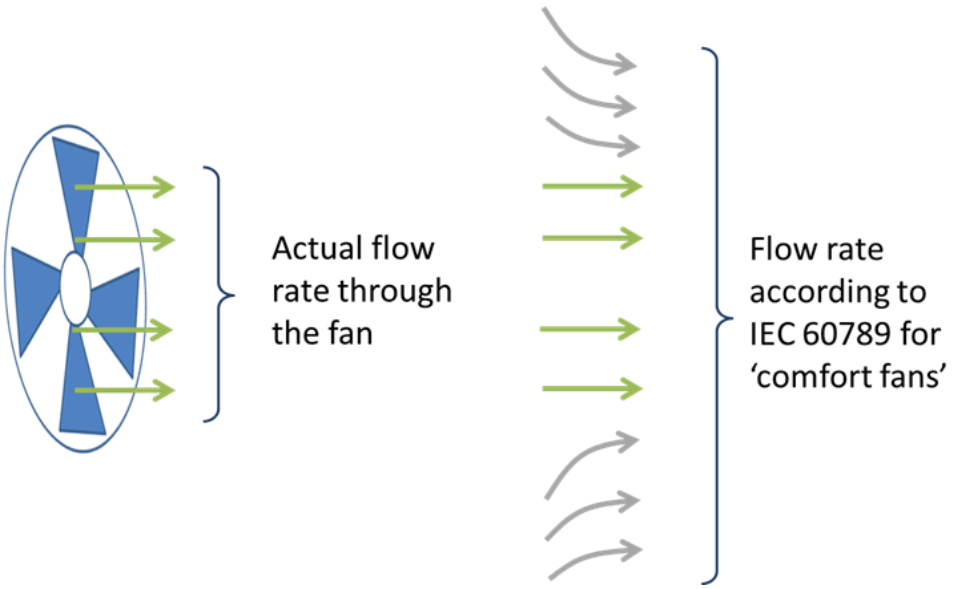
OF1

F1”

Actual flow rates through the filter and/or fans have been measured at LIFTEC, in a test bench designed according to **standard ISO 5801**.

The actual flow rate through the fans was measured without filters, yielding 690 m^3/h for BF1 and 1695 m^3/h for BF2.

It is **important** to note that these values are lower than the flow rates specified for comfort fans (typically, 4000-5000 m^3/h for 50cm fans), which are not the actual flow rate through the fan (without filter) but are measured according to standard IEC 60789 and actually represent the air motion far from the fan. This **must be taken into account**, as the actually flowing through the filter is much lower than the flow rate specified for comfort fans (typically, 5-6 times), with the risk of considerably overestimating the number of air changes per hour (instead of ACH=5, can easily be 1 or less…)



How should air purifiers be sized?

- The purifier must reach the recommended threshold of ACH=5 (air changes per hour). For 2.5 m high rooms, the capacity in m^3/h can be obtained by multiplying the room surface by 12.5. For example, 500 m^3/h are needed for 40 m^2.
- The purifier capacity must be measured in terms of its CADR (Clean Air Delivery Rate), equivalent to the product of the air flow rate actually flowing through the filter and its retention efficiency. In this report, a filtration efficiency of 85% has been applied for MERV13/F7 filters[1].

3. Filtration tests in rooms

The results of tests with several devices in rooms are presented in the first place.

The tests consisted in:

- Increasing particulate concentration in the room with smoke generated by burning incense sticks. Homogenize by stirring with a fan.
- With the door closed, start the device and record the evolution of concentrations measured with two analyzers (only one in the small room).
- The purifier was placed at the center of the room and the analyzers at the mid-point between the purifier and the walls.

Particulate concentrations were measured with two portable Temtop m2000 analyzers, which provide three readings: PM2.5, PM10 and total particulates. The evolution of the three values were very similar in relative terms (% with respect to the initial value), and also were the readings from the two analyzers installed at both sides of the purifier. So,

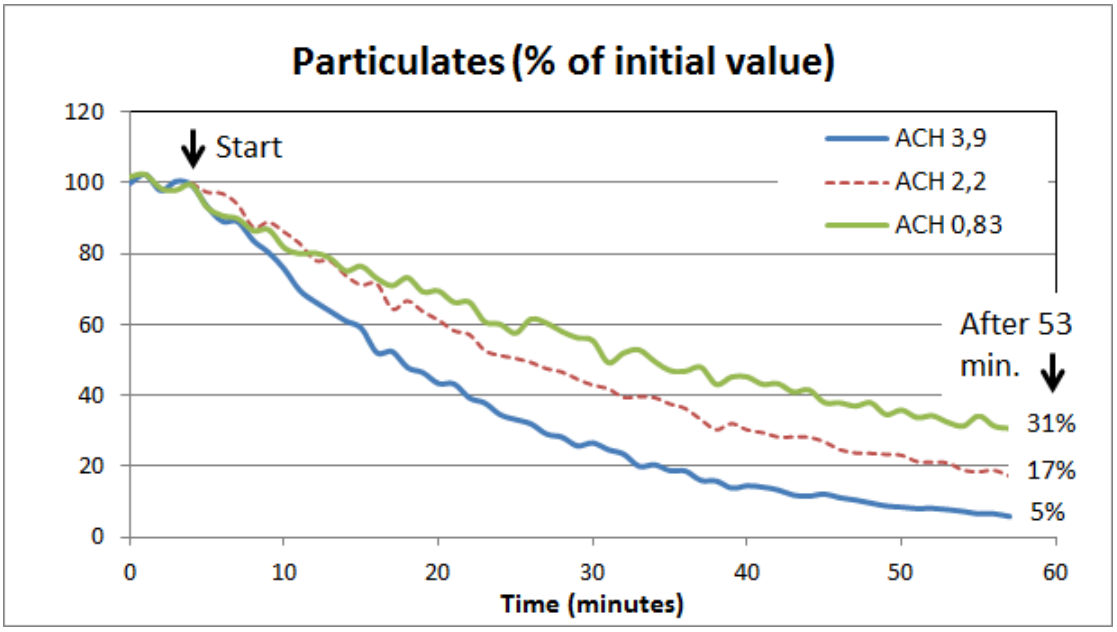
[1] This value coincides with the filtration efficiency in the range 1-3 microns. A more recent analysis concluded that the filtration efficiency for respiratory aerosols of MERV13/F7 filters exceeds 90%, but a more conservative factor of 75% is proposed.

the results are presented as the particulate concentration, calculated as the average of both instruments.

Tests with set OF1+F1" (center) in a 70 m^2 conference room. The particulate detectors have been placed at both sides.

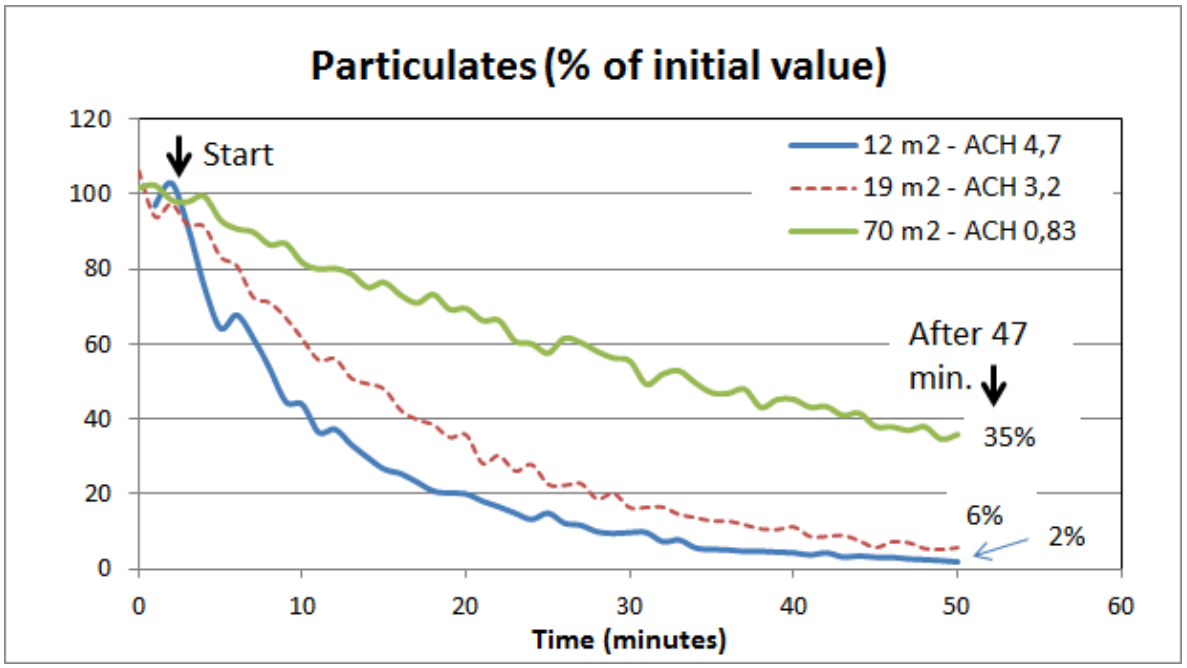
ACH is calculated by dividing the CADR by the room volume. For each purifier, CADR is calculated in this report by multiplying the measured flow rate of air exiting the filter by 85% (retention efficiency of MERV13/F7 filters, see tinyurl.com/CADRtests for more recent evaluations of actual filtration efficiency for respiratory aerosols).

The following graph shows the results for a 70 m^2 room, with fan BF1 (40 W), which yields ACH 0,83 in this room, and with OF1 (120 W) for speed settings 2 and 3 (ACH 2,2 and 3,9, respectively).



Results of air filtration tests with three different ACH in a 70 m^2 room.

The results with fan BF1 (40 W) installed in 3 different rooms are shown in the next figure. CADR is the same, resulting in three different ACH.



Results of filtration tests with assembly BF1+F1" (CADR=146 m^3/h) in three rooms of different sizes.

Some important conclusions can be highlighted from these tests:

- DIY purifiers are effective to capture particles and aerosols, as it could have been anticipated from its CADR values[2] (i.e., from measured flow rates, provided in the next sections, and the retention efficiency of the filter installed).
- For the same CADR, therefore, they are expected to provide the same particulate cleaning efficiency as other devices with more efficient filters (e.g. HEPA).
- The **correct selection of CADR** as a function of room size is a most critical decision when selecting an air purifier. We cannot assume that we are duly protected by just installing a device without verifying it provides the required flow rate of clean air. Devices with ACH below recommended values do not constitute a real protection: in that case, the purifier must be complemented with ventilation with fresh air until reaching the required ACH.

Since the flow rate of air passing through the filter (needed to calculate CADR) is a key parameter, not easy to obtain or estimate (as explained above, the filter drastically reduces the flow rate through the fan), we are providing in the following sections actual flow rates measured for different fan/filter combinations.

[2] Actually, particulate reduction rates were slightly lower than those estimated from its CADR by assuming that clean air gets instantly dispersed in the room. In some cases, it was verified that estimated and measured curves match almost exactly by just applying a correction factor of 0.9, ascribed to some imperfect mixing in this 70 m^2 space. This is related to the air motion inside the room and, hence, the same factor should be applied with commercial purifiers in the same room. In any case, this factor is not to be applied when sizing the purifier, which must be simply based on the recommended ACH and the device's CADR.

4. Air flow rate through the filter

The results are reported in terms of air flow rate passing through the filter. Respective CADR values are somewhat lower and easily obtained by multiplying air flow rates by the efficiency of the filter (85% is applied in this report for MERV13/F7, but more recent estimates can be found in tinyurl.com/CADRtests).

4.1 Flow rate of filtered air: Summary

- This section summarizes the main results and some general conclusions. More details in next sections.
- This table contains: ranges of flow rate and corresponding maximum room sizes for ACH=5. The intervals correspond to different fan/filter combinations and mounting methods, in all cases for the highest power setting of the fan.

	Flow rate (m^3/h)	m^2 Max.
BF1 + F1"	106-171	7-12
BF2 + F1"	385-497	26-34
OF1 + F1"	561-795	38-54

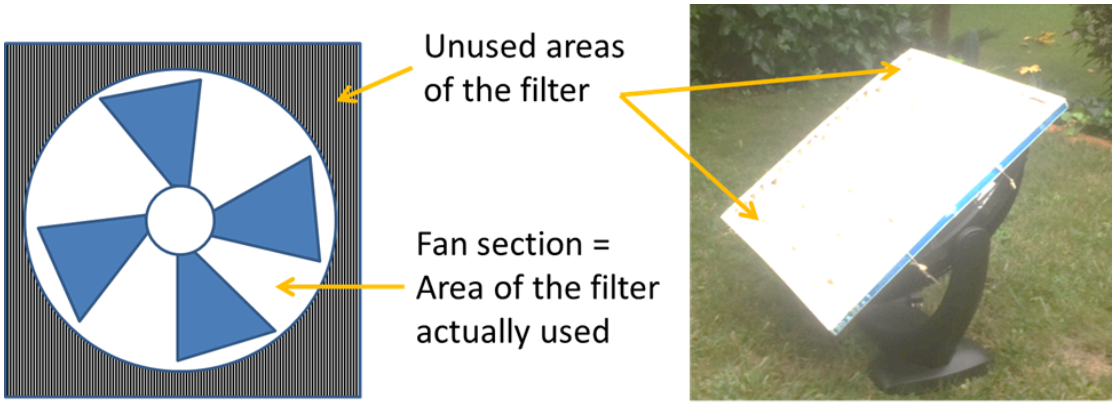
- Some preliminary conclusions from the results obtained so far:
    - It is important to pay attention to the flow rate actually obtained with respect to the room size. For example, BF1+F1" would not be enough for a 40 m^2 classroom (in that case, only ACH=1.7 would be reached).
    - For increasing flow rate, it is convenient to maximize the used area of the filter. This can be achieved by sealing around the filter or using square box fans of similar size. See explanation in next section.
    - For 'unsealed' assemblies, in which the full filter area is not utilized, the flow rate is lower (must be verified if sufficient for a given application). For that configuration, the flow rate remains about the same if the assembly is not very tight or even with gaps of several cm.
    - Not only box fans are valid for this use; open, shroudless fans can also provide similar performance.
    - The flow rates listed in the table above are for the highest power setting, but lower fan speeds could be used in order to reduce noise. Flow rates for other power settings provided below.
    - Flow rates measured for a MERV 13, 1" filter decrease by 3-5 times after mounting the filter and are typically between 5 and 10 times lower than flow rates specified for this type of comfort fans.

4.2 How should filter and fan be assembled?

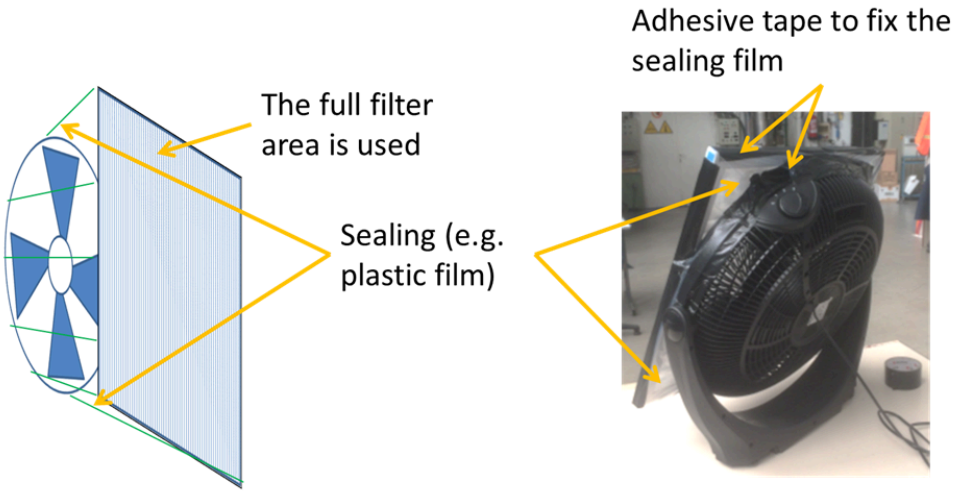
There are two main mounting methods:

1. The option commonly seen in posts and videos consists in just fixing the filter on the fan using adhesive tape or a lace (see option 1 in the next figure).
2. Another alternative is to seal the assembly, e.g. by fixing a plastic film with adhesive tape on the perimeters of the fan and of the filter, so that **the whole filter area gets included inside** (see option 2 in the next figure).

This figure shows both options for the assembly BF2+F1".



1. Filter fastened on fan, unsealed.

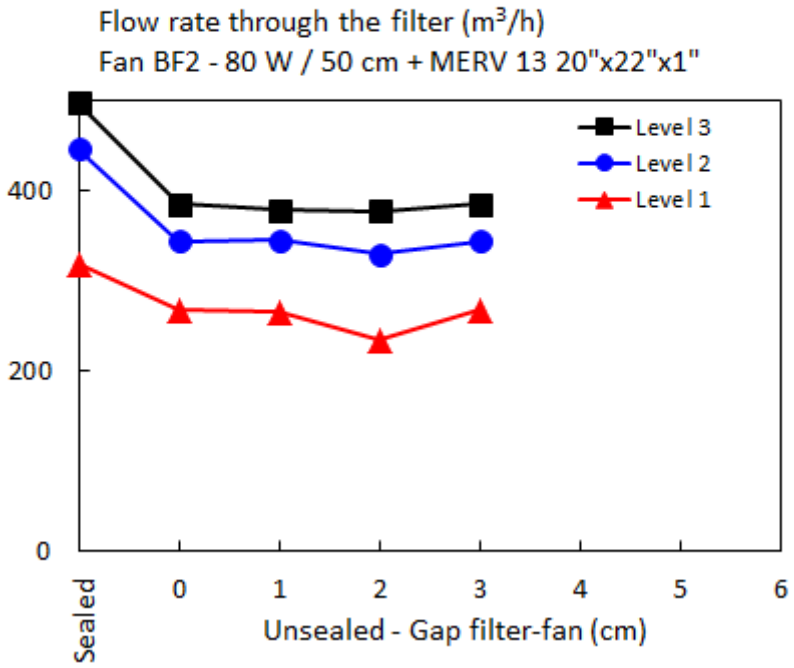


2. Filter sealed with fan, including the whole filter area inside.

The following graph displays the flow rates measured for the BF2+F1" assembly, for the three power settings of the fan and for different configurations: sealed and unsealed, with different gaps between fan and filter. It can be observed that:

- The sealed assembly yields higher flow rates, almost 30% higher than unsealed mountings. This is due to **using the whole filter area** (20”x22”=2840 cm^2), whereas if unsealed, only about the area of the fan is actually used (in this case, a circle of 50 cm, 1960 cm^2).
- The unsealed assembly yields similar flow rates, even with gaps of several cm between fan and filter. This might appear surprising, but can be explained by fluid mechanics considerations. In all cases, the backpressure induced by the fan on the inner side of the filter is about the same and the area of the filter actually utilized is approximately that of the fan (a 50 cm circle in this case), so yielding a similar flow rate.

  Hence, if the whole filter is not included inside the sealed volume, it is not important how tight the fan is mounted on the filter.



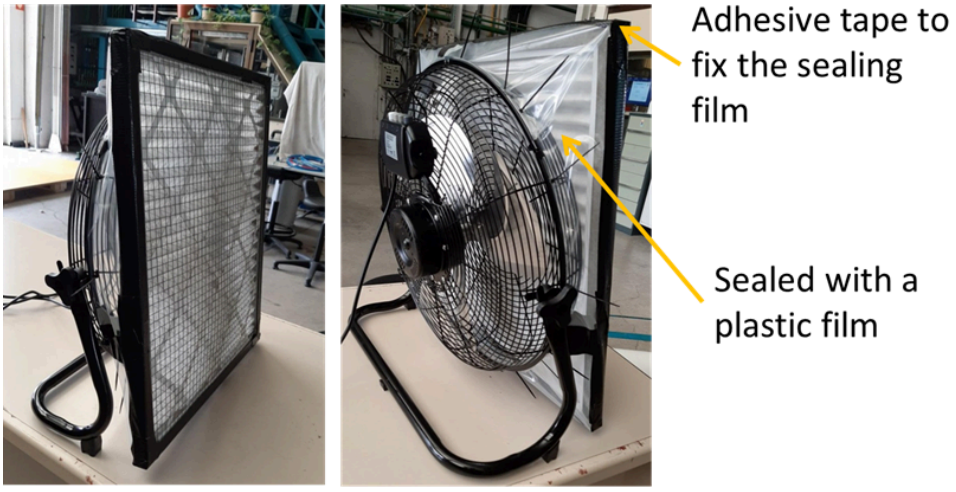
Note: for square box fans, like that in the figure, where fan and filter are about the same size, sealing is not very important or even needed because the whole filter area is already used. This type of fans are common in the USA, but not, for example, in Spain.

The same tests were conducted with the 120-W shroudless fan (OF1). The following figure shows the assembly sealed with a plastic film between filter and fan.

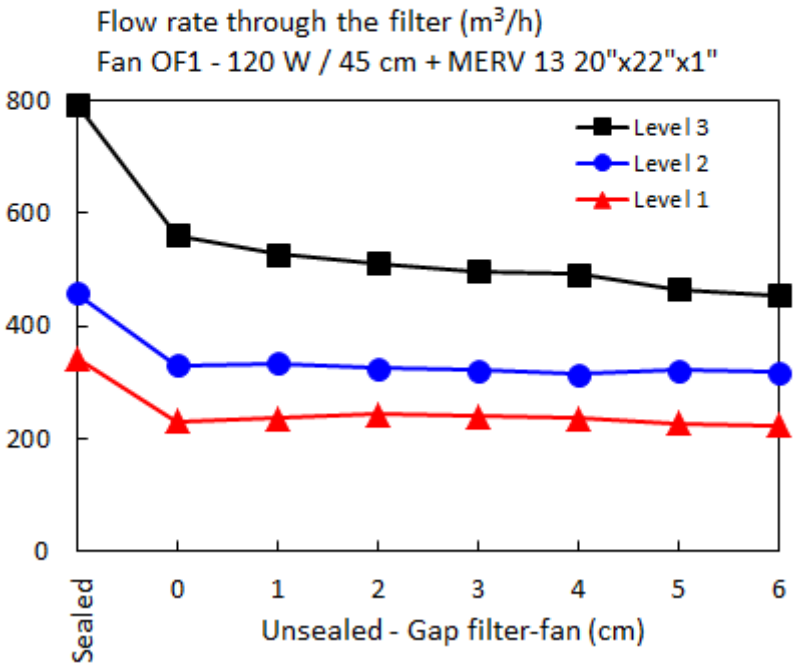
Similar observations as for BF2, with the following differences:

- Higher maximum flow rate: 795 vs. 497 m3/h, consistent with the higher fan power (120 vs. 80 W). Therefore, if the whole filter area is used, the fact of being an open-type fan is not a drawback.
- The difference between sealed and unsealed mountings is greater in this case: the flow rate increases by 42% due to the sealing, probably due to the smaller size of the fan (45 cm).

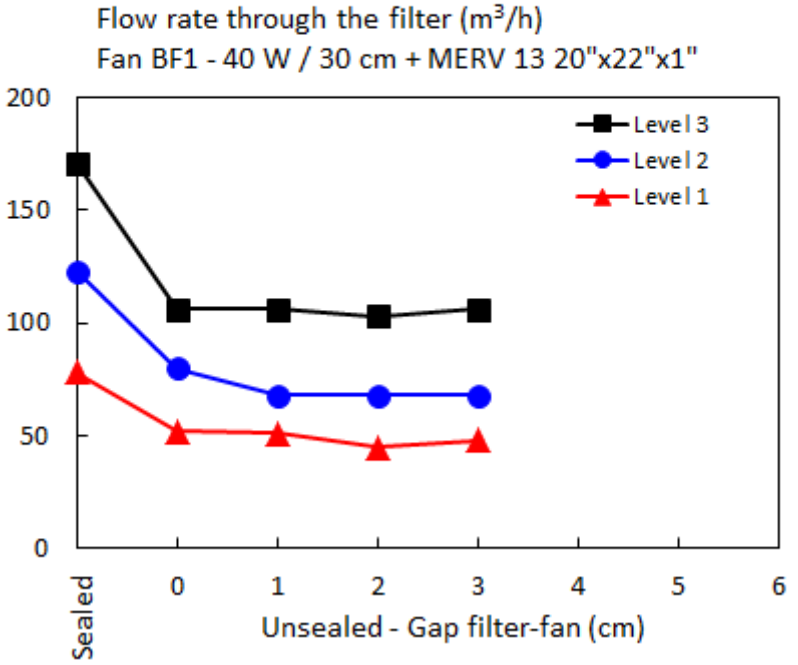
Again, the results confirm that the size of the gap between filter and fan does not significantly reduce the flow rate.



Sealed assembly OF1+F1”



Finally, the results for the box fan BF1 (40 “) are shown in the following graph. Same behavior as for the other fans, but in this case the increase in flow rate due to enclosing the whole filter inside the sealing film is even higher (61%). This is ascribed to the small size of the fan (30 cm), so that without sealing a large fraction of the filter area is not actually used.



4.3 Selection of power level in the fan

The graphs above include the flow rates measured for the 3 power settings of the respective fans and for the two mounting configurations. Numerical values are listed in the following tables.

Q (m^3/h) BF1 + F1"	Power level of the fan		
	1 (low)	2 (med)	3 (high)
Unsealed filter, gap=0	52	80	106
Sealed filter	78	123	171

Q (m^3/h) BF2 + F1"	Power level of the fan		
	1 (low)	2 (med)	3 (high)
Unsealed filter, gap=0 (left pict)	267	344	385
Sealed filter (right pic)	319	446	497

Q (m^3/h) OF1 + F1"	Power level of the fan		
	1 (low)	2 (med)	3 (high)
Unsealed filter, gap=0	231	330	561
Sealed filter	343	458	795

Setting (2) yields intermediate values, although closer to (1) or (3) depending on the fan. So, these values should be considered only as rough estimates, because actual differences among power settings will depend on the particular device.

Besides flow rate, noise can be also a relevant issue (e.g. in classrooms), which diminishes as a lower speed is selected. So, the optimal setting will depend on the application, but always keeping in mind that if, for example, the medium speed is selected, the flow rate will be lower than at the maximum power.

5. Various practical issues

5.1 Filter mounted on the back or on the front of the fan?

- In principle, it does not make a difference from the point of view of flow rate or fan operation. However, there can be other practical considerations.
- If installed on the back, the filter is supported on the fan, whereas if on the front, the air pressure on the inner side can push on and deform the filter. However, the filters usually include a wire grid, or they can be held with laces.
- In order to utilize the whole filter area with round fans, it is usually more convenient to mount the filter on the outlet. If on the inlet, the fan suction tends to push the filter on the fan, closing the gap between both and, hence, leaving the corners of the filter outside, so that the area actually used is lower and so will be the flow rate.

5.2 Does the device stir the air (and, perhaps, the virus) in the room or in adjacent spaces?

- Sometimes a suspicion (and concern) arises about the possibility that the device may stir the air (and the suspended pollutants) in the room, as it happens in conventional use of the fan.
- This does not happen, specially with no gap between filter and fan: with the filter mounted, it can be verified that the exiting flow is almost imperceptible (with a hand in front of the filter, you can barely notice it). Although the flow rate can be high enough, the speed of the air in front of the filter is very low (around 0.5-1 m/s, depending on the particular case). Very different from the jet generated by the fan (without filter), which is actually its purpose.
- If correctly used, like commercial purifiers, it is not expected to disperse contaminated air (and, if present, the virus) from one room to another. The device should be installed so that it discharges inside the same room. But even if oriented towards the door, the exiting air is already filtered.
- What if installed in front of a window? In that case, there is no point in installing the filter. Perhaps, place the fan so as to increase the flow of air from outside, but without a filter (outdoor air is supposed to be virus-free...).

5.3 Problems with 'contamination' of the filter?

- The filter, obviously, retains suspended particles (aerosols) and, if present, the virus they may contain. Exactly as in commercial purifiers. Apparently, the only difference could be that in commercial devices the filter is inside the case, but it is exposed in DIY purifiers.
- If the objective is, for example, to prevent children from touching the filter, a good solution could be to hang the device on the walls, like the fans in the picture (in that case, installing a filter is all what is needed to convert it into a DIY purifier). In this way, in addition, the blades are also out of reach.
- Or, alternatively, some type of protective shield or grill can be installed.

5.4 Overheating of the electric motor

- The reduction in the air flow rate through the fan due to the filter might lead to lower cooling and some overheating of the electric motor.

- Besides the thermal tests conducted on the fans (see below), the advice of experts[3] on the behavior and requirements for this kind of motors has been sought:
    - In Spain and Europe, the standard EN 60335-2-80 is compulsory for this type of fans. This standard covers all safety conditions that must be complied and, in particular, establishes that the device must have the necessary protections to guarantee that, under no circumstances, the motor can reach a level of overheating that could create risks for the user (e.g., temperatures above the limits for the materials, smoke emissions…). To this end, the motor must include some type of protection mechanism (e.g., a thermal fuse, which shuts off electric current when a certain temperature threshold is reached) or be designed to automatically prevent any kind of safety risk (e.g., high impedance coils). In this way, the devices must withstand limit conditions without any risk, even the complete blocking of the rotor (if some threshold is exceeded, the protection would act, e.g. by stopping the motor due to the breakdown of the thermo fuse).
    - Therefore, in any fan complying with that standard, as it is compulsory in Spain and Europe, the electric motor must include the necessary protections to prevent any possible risks due to potential overheatings.
    - It must be taken into account, however, that from the viewpoint of the applicable regulations, when the filter is installed on the fan, the assembly can be considered to be an air purifying device, which is regulated by the standard EN 60335-2-65, according to which it should be evaluated. In any case, this standard does not impose any additional requirement with respect to EN 60335-2-80 regarding the electric motor and its protections.
- Even though the accumulated experience on this kind of DIY purifiers is still limited, it can be noted that:
- There are no known cases of problems related to motor overheating in this type of fan+filter assemblies (mainly in the US).
    - Also, we have not detected problems of any kind in the tests conducted in his study up to date.
- Specific tests were conducted to measure motor temperatures under different operating conditions. The measurements were carried out by embedding a K thermocouple into a 2 mm deep hole drilled into the metallic motor body, so as to guarantee that the reading corresponds to the actual metal temperature (avoiding errors due to faulty thermal contact). The following image shows the thermocouple installed inside the motor body (the sensor has been inserted inside the metal and externally fixed with the putty visible in the picture).

[3] Dr. Juan Carlos Molina, technical responsible of the UO Projects and Electric Appliances (Laboratorio Central Oficial de Electrotecnia, FFII) and Dr. Sergio Llorente, from BSH Electrodomésticos España S.A., who are gratefully acknowledged for their full availability to share their time and expert knowledge.

- These tests are considered to be representative examples, although other cases could display some differences because it is actually a relatively complex problem (the motor temperature depends on the motor efficiency, on the flow induced around the motor by the rotating blades, on how exposed the motor is to the air flowing through the fan...).

Tests with BF2+F1":

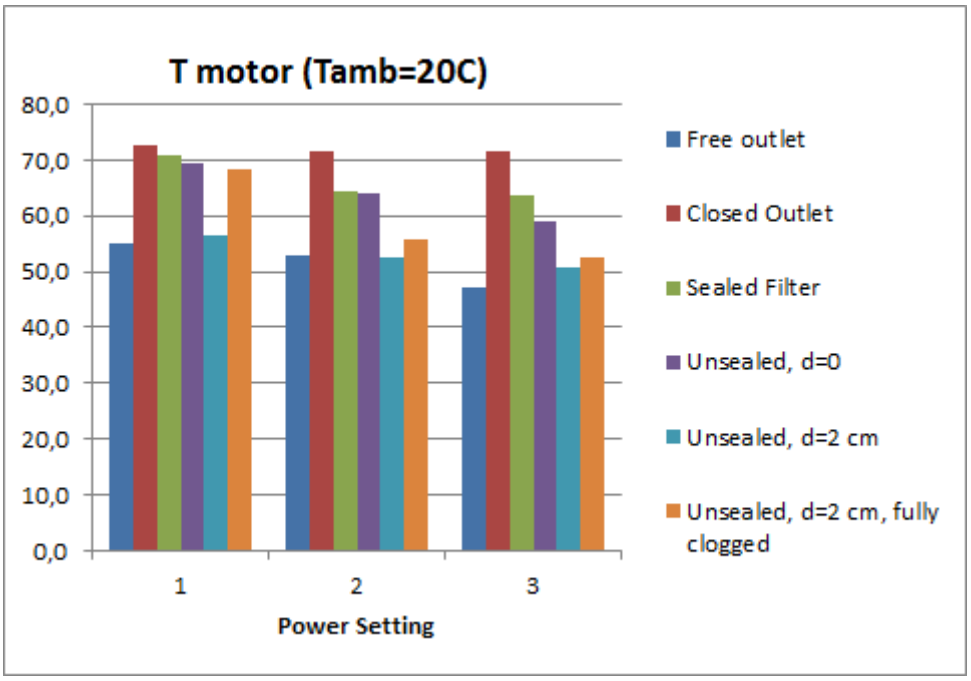
- The tests were performed on BF2 (80 W, 50 cm) and included:
    - the 3 power levels of the fan.
    - 3 different configurations: free fan outlet (as normally used at home), filter F1 mounted and fan outlet fully blocked with a plastic film.
- The following table displays the temperatures reached inside the motor body for the 3 conditions (corrected to a common ambient temperature of 20C):

T (°C), T ambient=20°C	Power level of the fan		
BF2 - 80W/50 cm	1 (low)	2 (med)	3 (high)
Free outlet	82,3	72,3	56,4
F1 mounted	72,1	65,3	65,9
Closed outlet	77,2	69,4	67,5

- These results suggest that:
    - The fan in normal use at level 1 displays the highest temperature (82,3 C). Since the manufacturer is expected to guarantee safe operation for a conventional utilization of the fan, the installation of the filter should not impose any further or dangerous strain on the motor. (We have not been able to extract any technical data or support from the manufacturer (!?), but they have not refuted this assumption, which might be a confirmation...).
    - On the contrary, for levels 1 and 2, the filter seems to even reduce the temperature reached by the motor with respect to a conventional use of the fan (free outlet). At least, this was the observed behavior for this particular fan.
    - In fact, the power consumption varied little among all cases (within 85-95 W), as a confirmation of the low efficiency of the electric motor at low speeds.

Tests with BF1+F1":

- The tests were performed on BF1 (40 W, 30 cm) and included:
    - the 3 power levels of the fan.
    - 6 different configurations:
        - Free outlet (conventional domestic use)
        - Blocked outlet (fully closed with a plastic film), to study the limit condition in which no net flow rate passes through the fan.
        - Sealed filter (as described above).
        - Unsealed filter, gap d=0 (filter fastened against the fan)
        - Unsealed filter, d=2 cm (there is a gap of 2 cm between the front of the fan and the filter).
        - Unsealed filter, d=2 cm, with 'fully clogged filter', to simulate a hypothetical situation in which the filter would be completely clogged, without any air flowing through the filter. For that, the filter was covered with a plastic film.
- The temperatures measured in the motor after reaching a steady thermal state are displayed in the following graph. In order to avoid effects due to changes in room temperature, the values have been corrected to a common ambient temperature of 20C.



- In this case, the highest temperatures were obtained in the conditions with the lowest flow rates through the fan: highest values for blocked outlet, followed by clogged filter, etc. In the case with unsealed filter, d=2 cm, the temperatures are very similar to those with a free outlet.

- In any case, it should be noted that all values with the filter installed are lower than for blocked outlet. Although further confirmation might be needed, this limit case appears as a situation that could perfectly occur in normal use and to which the device should be tolerant (in conventional domestic use, the fan outler can sometimes be covered by, for example, a piece of cloth...).
- As for BF2, the highest temperatures were recorded for the minimum power setting. Most probably, this can be due to the low efficiency of this type of electric motor in this condition. Therefore, it seems advisable not to work at the lowest speed but rather select settings 2 or 3 (depending on the best trade between flow rate and noise).